Novel Braking Resistor Models for Transient Stability Enhancement in Power Grid System

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Abstract- **Braking resistor (BR) is one of the effective methods to improve the transient stability of synchronous generators. In this work, two new braking resistor models, one consisting of thyristor rectifier and the other consisting of a combination of diode rectifier and chopper, are proposed, and their performance is compared with the existing thyristor controlled braking resistor. Comparison is made in terms of the speed performance indices, number of components used, heat loss and harmonics analysis for each proposed model and the existing model. The effectiveness of the proposed methodology is tested through Matlab/Simulink simulations considering both balanced and unbalanced temporary and permanent faults in a single generator power grid system. Simulation results indicate that the transient stability performance of the proposed methods is comparable to that of the existing model. Moreover, the proposed models use a single unit of BR that might lead to cost reduction of BR. Therefore, the proposed models can be considered as an alternative to the existing model for improving the transient stability of the power system.**

Index Terms — **Braking resistor (BR), chopper controlled braking resistor (CRCBR), PID controller, rectifier controlled braking resistor (RCBR), thyristor controlled braking resistor (TCBR), transient stability.**

I. INTRODUCTION

In order to make the existing power grid system self-sufficient, reliable and more efficient, continuous research is going on in different areas of grid systems and its related elements. Transient stability enhancement is related to the ability of the power system to maintain synchronism when subjected to severe disturbance, such as short circuit on transmission line. It depends on both the initial operating state of the system and the severity of the disturbance [1-3]. Advancement in power grid system such as integration of new non-renewable generating sources and addition of flexible AC transmission devices make it more important to maintain transient stability, of the large interconnected system. Various control strategies to improve the transient stability are reported in the literature. Braking resistor (BR) is one of the most efficient and widely used external control methods to improve the transient stability [4-17].

BR is a dummy load that is added to electrical machines to decrease the speed as required for short duration of time, and is removed from the machines when the speed is reduced to a desired level. Many applications of BR can be found in the literature, such as braking device in large power grid system to reduce the speed of the synchronous generators [4-16], series braking resistors to improve transient stability of low inertia small distributed generators [17], electrical braking for improving wind turbine system performance [18-19], braking device to maintain sub-synchronous resonance of the power grid system [20], etc.

Fuzzy controlled braking resistors are designed in [7-15] for providing better control of BR unit for switching in and out from the grid system to improve the transient stability of the system. It is designed with a fuzzy controller used to generate firing angle, α, needed to trigger the thyristors of the thyristor controlled braking resistor (TCBR) by using the change in speed of respective synchronous generator as an input to the controller. TCBR per phase model is constructed as back-to-back connected thyristors with BR in series. It means that it uses one BR unit for each phase to improve the transient stability. No work is found in the literature regarding use of single unit of BR for three phase power grid system for the improvement of transient stability.

In this paper, two new BR models, namely rectifier controlled braking resistor (RCBR) model and chopper rectifier controlled braking resistor (CRCBR) model are proposed. Novelty of these models is that both models use one unit of BR as compared to three units of BR in the existing TCBR model for the three phase system. Utilization of proposed models might lead to reduce overall size as well as cost of the overall BR model unit. RCBR model may lead to reduced heat loss whereas CRCBR model may lead to reduced harmonics. The performances of the proposed models are compared and analyzed with that of the existing model.

In this work, the controller is designed, for all models, with a logic that the speed deviation of synchronous generator is taken as an input and the triggering pulses are generated as an output for respective model. Models are implemented by using MATLAB/Simulink software, and are tested considering both balanced and unbalanced temporary and permanent faults in a single generator power grid model. Simulation results for all models are compared and analyzed, and indicate that the proposed models can be considered as an alternate solution for improving the transient stability for interconnected power generation system, although an exact market price for new models is not yet determined.

The paper is organized as follows. In section II, the power system model used for simulating new and existing models is discussed. In section III, braking resistor models are described

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with their construction elements and parameters. In section IV, the controller design using proportional-integral-derivative (PID) controllers for each model is discussed with related parameters. Section V consists of simulation results and the discussion made for all three models. In section VI, the conclusions are drawn with mention of future work

II. POWER SYSTEM MODEL FOR TRANSIENT STABILITY ANALYSIS

The single generator power grid system model [12] is used in this paper for implementing all three BR models for the improvement of transient stability. It is shown by a single line diagram in Fig. 1. The system model consists of a synchronous generator (SG, rated as 1000MVA, 20KV, 50 HZ) feeding an infinite bus through a step up transformer rated as (20KV/500KV) and a double circuit transmission line system. Circuit Breakers (CB) are connected in as shown in the single line model as a protection device to disconnect the respective faulted line. The BR model is connected on the high voltage side of the step up transformer for each model. The operating parameters of the synchronous generator used for the simulation are shown in the Table I. The control model blocks of the automatic voltage regulator (AVR) and governor (GOV) used for this work is taken from [12] and shown in Figs. 2 and 3, respectively.

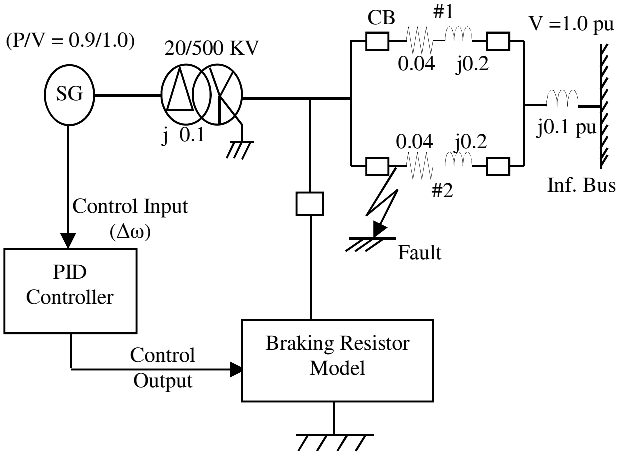

Fig. 1. Single generator power system model.

TABLE I
GENERATOR PARAMETERS

MVA	1000
r_a [pu]	0.003
x_a [pu]	0.139
X_d [pu]	1.79
X_q [pu]	1.71
X'_d [pu]	0.169
X'_q [pu]	0.228
X''_d [pu]	0.135
X''_q [pu]	0.20
X_0 [pu]	0.13
T'_{do} [s]	4.30
T'_{qo} [s]	0.85
T''_{do} [s]	0.032
T''_{qo} [s]	0.05
H [s]	2.894

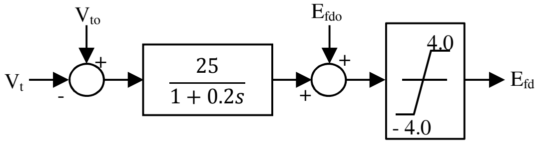

Fig. 2. AVR model.

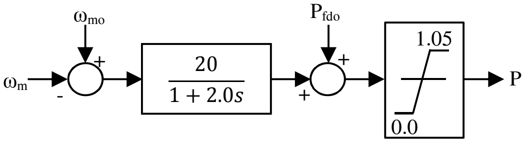

Fig. 3. GOV model.

III. NEW MODELS DESIGN FOR BRAKING RESISTOR

As mentioned earlier, the key element of a feedback BR model is its controlling switch. Two new BR models proposed in this paper uses highly efficient power electronic models that convert AC current and voltage into DC current and voltage. The DC voltage and current have their own advantages over AC current and voltages, such as they reduce harmonic current and ripples and decrease heating of BR. All models are triggered by triggering pulses generated as an output, which is discussed in next section. For all models discussed in this work, thyristors and diodes are assumed to be rated as 1000 MVA, 6.6 KV, therefore a step down transformer (500KV/6.6KV) is implemented to connect BR model on high voltage side of generator step up transformer. A brief description of all three models is given as follows.

A. Rectifier Controlled Braking Resistor (RCBR)

A simple design for this proposed model, shown in Fig. 4, consists of a rectifier circuit in series with single BR unit. The thyristor rectifier circuit consists of six thyristors forming a switch for BR. The three phase rectifier unit coverts AC voltage into DC voltage, which is fed to the BR unit. The DC voltage, V_{DC}, across BR is calculated by using (1) and the respective value of BR is calculated by using (2) for rated voltage of 6.6 KV and rated power of 1000 MVA and is shown in Table II.

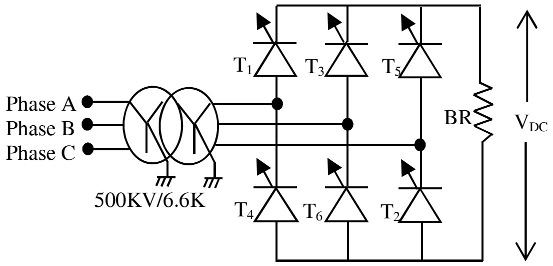

Fig. 4. Rectifier controlled braking resistor model.

$$V_{DC} = \frac{3\,V_m}{\pi}\cos\alpha\,(V) \tag{1}$$

$$R = \frac{{V_{DC}}^2}{P}\,(\Omega) \tag{2}$$

where, V_{DC} is voltage across BR, V_m is the peak of the line voltage given to the thyristor rectifier, α is firing angle for thyristor, P is total rated power of grid system, and R is the value of BR unit used to reduce the speed of generator at rated power.

B. Chopper Rectifier Controlled Braking Resistor (CRCBR)

This proposed model is a combination of uncontrolled diode rectifier and chopper with better benefits over RCBR model as mentioned in [21-23]. A simple design for this model, shown in Fig. 5, consists of three phase uncontrolled diode rectifier, chopper switch (CS) and single BR unit. The controlling switch for BR in this model consists of a thyristor. A capacitor (C) is needed to maintain minimum voltage across the diode rectifier. When the voltage across capacitor increases beyond its rated capacity, extra voltage is dissipated as heat energy through BR. The DC voltage, V_{DC}', across the capacitor is calculated by using (3) and the voltage across BR, V_{DC}, is calculated using (4) for rated voltage of 6.6 KV and rated power of 1000 MVA.

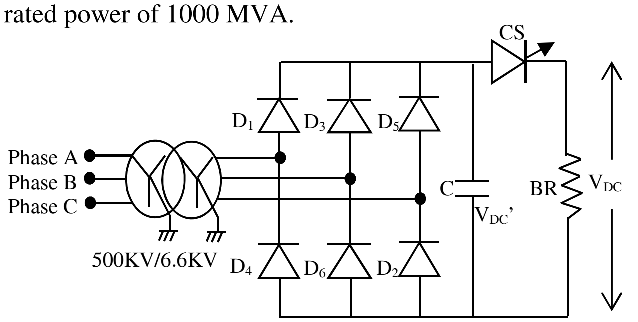

Fig. 5. Chopper rectifier controlled braking resistor model.

$$V_{DC}' = \frac{3\,V_m}{\pi} \qquad (3)$$

$$V_{DC} = d\,V_{DC}' \qquad (4)$$

where, V_m is the peak of the line voltage given to diode rectifier, V_{DC}' is the DC voltage across the capacitor, and also the input voltage to the chopper, d is the duty cycle of chopper, and V_{DC} is the voltage across the BR.

C. Thyristor Controlled Braking Resistor (TCBR)

This model is used as a reference model to provide a comparative study with proposed models. It is a simple model [7-16], shown in Fig. 6, and consists of two thyristors, namely T_1 and T_2, connected back-to-back in series with the braking resistor unit, BR, for a per phase system, and hence a total of three sets of TCBR models are implemented for a three phase power grid system. Fig. 6 shows the line diagram of a single phase TCBR model, therefore three phase step down transformer required for implementing the existing model is not shown here. The back-to-back connected thyristors are acting as a controlled switch for the BR unit. The detailed modeling of thyristors is explained in [15].

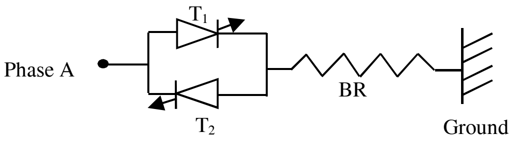

Fig. 6. Thyristor controlled braking resistor model.

It is important to note here that the BR values in Table II are given with respect to 1.0 pu value of the BR which is considered in this work in order to obtain the best system performance for all three BR models.

TABLE II
ACTUAL VALUES OF BR FOR DIFFERENT BR MODELS

Model type	BR value (Ohms)
RCBR	0.07952
CRCBR	0.01988
TCBR	0.04356

IV. CONTROLLERS FOR BRAKING RESISTOR MODELS

Three different BR models, discussed in this paper, needs different switching pulses for triggering respective thyristors. A simple controller, shown in Fig. 7, is designed to generate respective triggering signals for each model. It consists of a classical proportional-integral-derivative (PID) controller, a limiter and a mathematical block with a constant, *K*. The PID control block structure is shown in Fig. 8. The controller takes change in speed of synchronous generator as input and gives an output as a constant, *A*, that is fed to the limiter block. A limiter is used to limit the output of PID controller within the range L_{Min} and L_{Max} as required by each model. The final control output from the controller block is fed to the respective switch of each model.

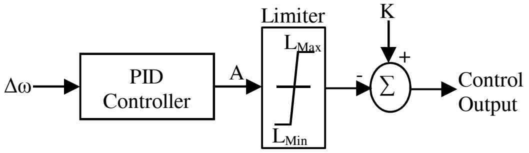

Fig. 7. Controller block.

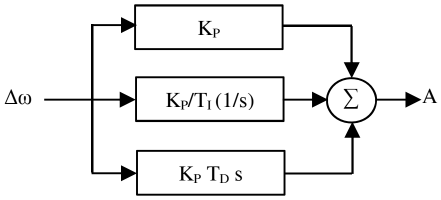

Fig. 8. Block diagram of PID controller.

For RCBR model shown in Fig. 4, the controlled thyristor rectifier model needs firing angle, α, to trigger the rectifier circuit. For full conduction of BR firing angle, α, for thyristors should be 0□ and for no conduction α should be maintained at 90□. Therefore, the controller block should generate control output as firing angle, α, which varies between 0□ and 90□.

For CRCBR model shown in Fig. 5, the uncontrolled diode rectifier chopper circuit needs duty cycle for triggering the chopper switch, CS, consisting of thyristor. Although the controller block generates control output as duty cycle, *d*, which varies between 0 and 1, the actual duty cycle for the chopper operation varies between 0.5 and 1.

Similarly, for the TCBR model shown in Fig. 6, there are two thyristors connected back-to-back which controls the switching operation of braking resistor. Hence, for the positive half cycle the thyristor, T_1, operates, and for the negative half cycle the other thyristor, T_2, operates. For full conduction of BR, firing angle, α, should be 0° and for no conduction α should be 180°. Therefore, the controller block should generate control output as firing angle, α, which varies between 0° and 180°.

As mentioned earlier, each BR model is implemented with the same controller, but as triggering is different for each model, different controller parameters are required to generate required control output. Different parameter values, K_P, T_I, T_D, L_{Min}, L_{Max}, and K, as required by controller of each model, are shown in Table III. The control output from the controller is sent to BR models only when the rate of change of speed of synchronous generator is greater than or equal to 3 rpm or 0.001 pu. This limit for controller is chosen such that the power grid system gets stabilized as quickly as possible, and the BR is not inserted into power grid system for a long time to avoid heating of BR.

TABLE III
CONTROLLER PARAMETERS FOR DIFFERENT MODELS

Model type	K_P	T_I	T_D	Limiter		K
				L_{Max}	L_{Min}	
RCBR	4.5	0.01	0.0001	90	0	90
CRCBR	1.0	0.0001	0.0001	1	0	1
TCBR	10	0.0001	0.01	180	0	180

V. Simulation Results And Discussion

In this work, simulations for transient stability study are done by using MATLAB/Simulink software. Both balanced (3LG: three phase-to-ground and 3LS: three-phase short circuit) and unbalanced (2LG: double line-to-ground, 2LS: line-to-line, and 1LG: single line-to-ground) temporary and permanent faults are considered on the line #2 of the power system model shown in Fig. 1. For temporary fault, fault occurs at 0.1 sec and cleared at 0.6 sec, CB opens at 0.2 sec and closes at 1.2 sec. For permanent fault conditions, the CB reopens at 1.3 sec, while the other simulation conditions are the same as the temporary faults. The time step and simulation time are chosen as 0.00005 sec and 10 sec, respectively. Analysis of model performances is done in three categories, namely performance analysis, cost analysis and heat loss and harmonics analysis.

A. Performance Indices Analysis

For analyzing the effectiveness of BR models, the performance index based on generator speed deviation is considered, and shown in (5).

$$\Delta\omega_c(radian) = \int_0^T |\Delta\omega|\, dt \tag{5}$$

where T is the simulation time of 10.0 sec, $\Delta\omega$ is change in speed of synchronous generator and $\Delta\omega_c$ is speed performance Index. The smaller the $\Delta\omega_c$ is, the better the performance of model is. The performance of the BR models is analyzed for temporary and permanent faults as follows.

a. Temporary Fault Analysis

Speed index values, calculated by using (5), for temporary fault (balanced and unbalanced conditions) with and without BR models are shown in Table IV. It can be seen from Table IV that the proposed CRCBR model's performance is better than the other model's performance. The speed index values for TCBR and RCBR models are comparable for all fault conditions. It can be seen from speed responses shown in Figs. 9 and 10 for 3LG and 1LG faults that all three models are stabilizing synchronous generator within small period of time without exceeding the speed limit set at 0.001 pu by the controller. The speed curves with respect to speed index, is varying accordingly for all models. The speed responses of CRCBR model show better performance as compared to other two models. The RCBR model speed curves show slow decay as compared to TCBR model speed curves for both 3LG and 1LG faults. The total power consumed by BRs is shown in Table V which implies that the power consumed by CRCBR model is more as compared to RCBR and TCBR models. The total power consumed by RCBR model is less as compared to other models.

b. Permanent Fault Analysis

Speed index values, calculated by using (5), for permanent fault (balanced and unbalanced conditions) with and without BR models are shown in Table VI. It can be seen from Table VI that the proposed CRCBR model's performance is better than the other models' performance. The speed index values for TCBR and RCBR are comparable for all fault conditions. It can be seen from speed responses in Figs. 11 and 12 for 3LG and 1LG faults that all three models are stabilizing synchronous generator within small period of time without exceeding the speed limit set at 0.001 pu by the controller. The speed curve of CRCBR implies better performance as compared to other models. The RCBR model speed curves shows deviation from the TCBR model speed curve. The total power consumed by BRs is shown in Table VII which implies that the power consumed by RCBR model is less, whereas power consumed by CRCBR model is more.

B. Cost Analysis

The important feature of the proposed models, as mentioned earlier, is that the number of BR units is decreased to one from three for a three-phase system because of the switch designs of the proposed models. All components used in the switch design of the existing and proposed models are shown in Table VIII. It can be seen that the BR unit is reduced to one for the proposed models. However, few components, such as the capacitance bank and diodes, are not used in the TCBR model, while they are used for designing the other two models. Table II shows that the BR value for each model is different, but due to reduced number of BR units, the overall size will be reduced and the proposed models provide a simultaneous control on three phases with single switch. The number of elements as well as their ratings, used to design the existing and proposed models is nearly the same.

The best feature would be the reduction of the cost of BR units. By getting an exact market price of different elements used for construction of the proposed and existing BR models, the cost comparison can be done for two BR units replaced with new switches.

TABLE IV
SPEED INDEX VALUES FOR TEMPORARY FAULT

Types of faults	With no BR	With TCBR	With RCBR	With CRCBR
3LG	24.32	11.37	13.62	10.27
3LS	23.92	10.98	13.49	10.08
2LG	17.24	6.793	10.87	5.862
2LS	9.163	6.846	7.723	5.148
1LG	7.447	5.748	6.06	4.926

TABLE V
TOTAL POWER CONSUMED (IN WATTS) BY BR FOR TEMPORARY FAULT

Types of faults	TCBR model	RCBR model	CRCBR model
3LG	1.392×10^{8}	8.976×10^{7}	1.755×10^{8}
3LS	1.400×10^{8}	8.835×10^{7}	1.806×10^{8}
2LG	1.077×10^{8}	6.401×10^{7}	1.332×10^{8}
2LS	7.596×10^{7}	3.299×10^{7}	9.932×10^{7}
1LG	4.121×10^{7}	1.548×10^{7}	8.189×10^{7}

TABLE VI
SPEED INDEX VALUES FOR PERMANENT FAULT

Types of faults	With no BR	With TCBR	With RCBR	With CRCBR
3LG	37.01	18.03	18.23	15.51
3LS	36.05	17.74	18.03	15.66
2LG	35.06	12.13	16.11	10.85
2LS	18.41	9.592	11.56	9.419
1LG	15.68	8.791	10.75	8.801

TABLE VII
TOTAL POWER CONSUMED (IN WATTS) BY BR FOR PERMANENT FAULT

Types of faults	TCBR	RCBR	CRCBR
3LG	2.683×10^{8}	1.329×10^{8}	3.358×10^{8}
3LS	2.659×10^{8}	1.310×10^{8}	3.213×10^{8}
2LG	2.682×10^{8}	1.299×10^{8}	3.598×10^{8}
2LS	1.325×10^{8}	5.136×10^{7}	2.729×10^{8}
1LG	7.939×10^{7}	3.827×10^{7}	2.060×10^{8}

TABLE VIII
COMPONENTS FOR THREE PHASE BR MODELS

Components	TCBR	RCBR	CRCBR
Thyristors	6	6	0
Diodes	0	0	6
Capacitance	0	0	1
BR Units	3	1	1

C. Heat Loss and Harmonics Analysis

Heat losses occurring due to heating of BR unit for proposed models reduced to approximately one-third as compared to heat losses occurring in the existing TCBR model, as only one unit of BR is used for the proposed models. Tables V and VII imply that the total power consumed by the CRCBR model is more as compared to that by other two models. So, the heat loss for the CRCBR model would be more. The BR unit performance is less affected by increase in temperature of BR unit [12] for transient stability operation; therefore, more heating of proposed model's single unit BR as compared to existing model's three units of BR will not affect the transient stability performance of respective models.

It is implemented from [21-23] that the CRCBR models are more efficient as compared to the RCBR models as they generate a load current with reduced ripple and generate less current harmonics. The RCBR and CRCBR switch performance is better than the back-to-back connected thyristors performance, as earlier switches provide a three-phase control simultaneously as compared to the later.

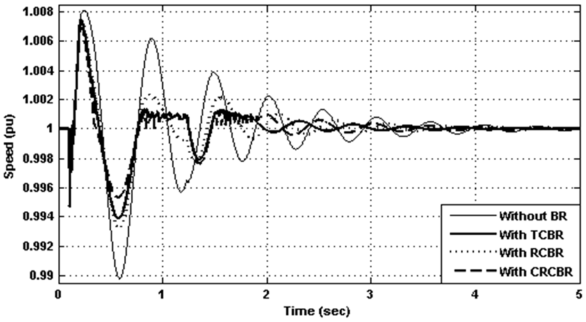

Fig. 9. Speed curves for 3LG temporary fault.

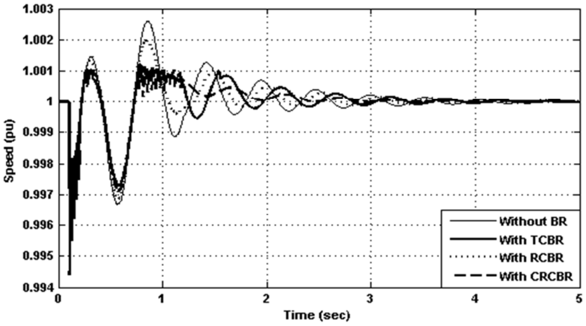

Fig. 10. Speed curves for 1LG temporary fault.

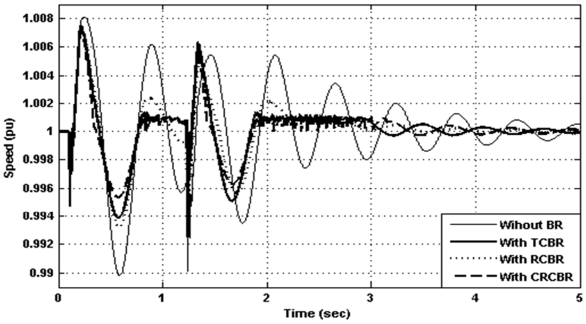

Fig. 11. Speed curves for 3LG permanent fault.

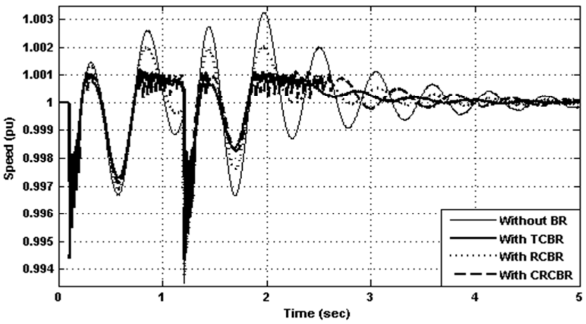

Fig. 12. Speed curves for 1LG permanent fault.

VI. CONCLUSION

This paper proposes new RCBR and CRCBR models with an advantage of reduced number of BR units which may lead to reduced overall size and cost of BR model. Speed curves and speed indices calculated for both temporary and permanent faults for all balanced and unbalanced fault conditions imply that the CRCBR model is better than the other models, whereas heat losses by the CRCBR model would be higher due to higher power dissipation in BR as compared to other models. Therefore, it can be concluded that the proposed models are alternate solutions to the existing BR model considering few trade off conditions, such as speed index, cost, heat loss and harmonics.

In future, exact cost analysis will be done to show exact benefits that can be achieved by using new proposed models. These models will also be tested for a large multi-machine power grid system.

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